

## REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) A special purpose wind tunnel designed to test the fluid mechanical and heat transfer properties of ceramic matrix structures was designed, constructed, and subjected to performance testing. The facility was completed and assembled in early 2002. Two problems occurred during the initial testing phases of the facility. A persistent leak that limited the pressures that could be achieved was solved by remachining a flange surface and installing large o-ring seals. A pumping bearing problem is being addressed by the pump manufacturer under warranty. Direct numerical simulation calculations were initiated. This work is aimed at predicting the effectiveness of transpiration cooling for a turbulent boundary layer at low Reynolds number.					
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1. 在“          ”处填上恰当的词语。  
 2. 用“——”画出描写环境的句子。

JUN 11 2003

**Basic Research Problems in Mechanics and Heat Transfer for  
Integrally Woven, Transpiration Cooled Ceramic Composite  
Turbine Engine Combustor Walls**

AFOSR Contract Number F-49620-00-1-0272

**Final Report for the period May 1, 2000 through May, 2003**

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June, 2003

## 1. Motivation for the Research

New integrally woven ceramic matrix composites which can be transpiration cooled offer the prospect of substantial combustion system gains. Very little is known about the fluid mechanics and heat transfer for such transpiring surfaces at the flow field conditions of gas turbine applications. Advanced simulation including Direct Navier Stokes simulation and much less computationally intensive design tools, which have been validated against well defined experiments, are needed to exploit the potential of this new technology. Research on transpiration cooling in general and for this application in particular is important because it offers the potential to reduce the cooling air requirements for the combustor wall of a gas turbine by 50% as well as potentially allowing changes to the geometry that could reduce size and emissions and overall weight of the engine. Similarly the technology has substantial potential benefits for hypersonic systems. In all these cases these benefits will be realized only when the performance in well characterized experiments is understood, parameters have been optimized, and results from such experiments are used for the validation of design tools. Figure 1 summarizes the basic research problems which initially motivated this research and the companion materials research by Rockwell Science Center, also supported by AFOSR.

### Basic Research Problems in Mechanics and Heat Transfer for Integrally Woven, Transpiration Cooled Ceramic Composite Turbine Engine Combustor Walls

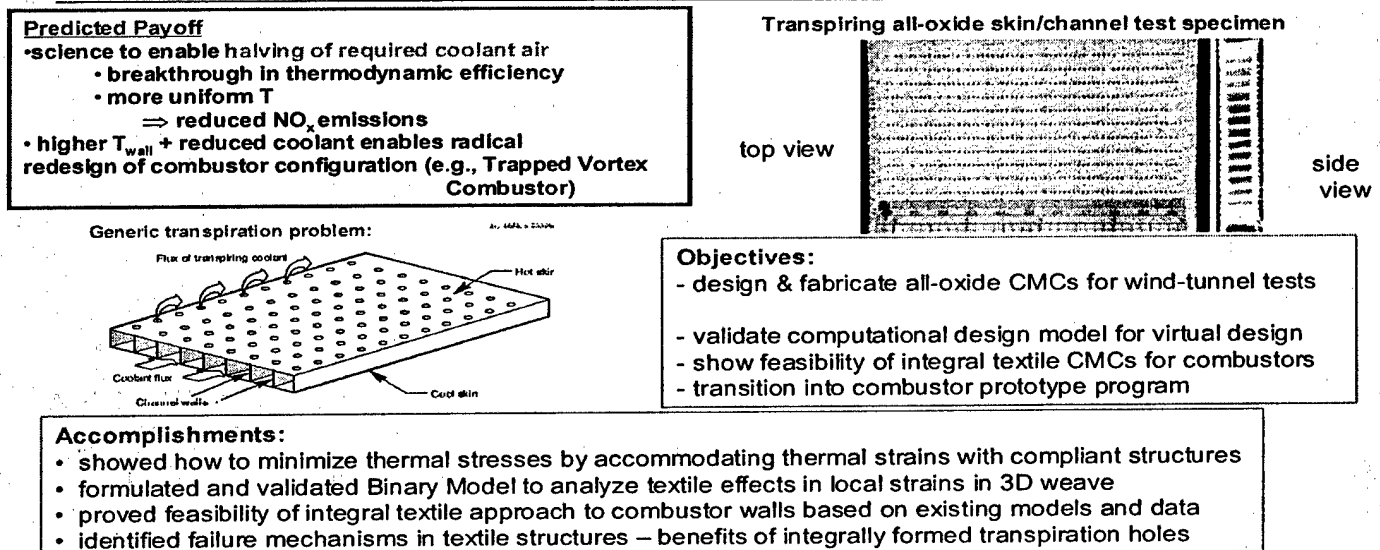


FIGURE 1

## **2. Objectives in the original proposal**

### **Year 1**

1. Design and build a special purpose wind-tunnel with a test section designed to accommodate 10cm x 10cm transpiring ceramic matrix structures provided by RSC.
2. Provide preliminary point measurement results on the cooling effectiveness of such structures at Representative conditions (Re, velocity ratio, etc.) and compare with predictions obtained from further literature studies.

### **Year 2**

1. Develop liquid crystal and other field measurement techniques to obtain heat-transfer and surface temperature data.
2. Commence CFD studies with Professor Martinelli and a graduate student.

### **Year 3**

1. Explore effects of key parameters (Re, velocity ratio, density ratio, turbulence intensity and Turbulence length scale).
2. Obtain data at modest Re and large scales to explore underlying physics and to provide Benchmark data against which to compare with a DNS calculation.

## **3. Concept for the research**

The basic idea behind the research and the special purpose wind tunnel that has been built is to be able to use specimens of woven ceramics (or other materials) which are geometrically identical with those in applications, to then duplicate the Reynolds number of the cooling gas and boundary layer flow and duplicate the near wall density and velocity ratio for transpiration cooling. The ratio of cooling gas temperature to free-stream recovery temperature should be the same as it is for flight applications but these temperatures in the facility would be chosen to be a fraction of those in the flight application so as to allow detailed flow measurement and visualization. In particular, the approximate temperatures of interest for the gas turbine combustor are respectively 1000K, 1500K, 2500K for the cooling flow, the combustor surface and the combustor free stream and the pressure of interest is up to 60 atmospheres. The new facility would duplicate the corresponding densities by operating at 200K, 300K and 500K for the cooling air, wall temperature and free stream and operate correspondingly at a pressure up to 12 atmospheres. In fact the facility has been designed to operate from 0.1 to 25 atmospheres and with a free stream temperature from 100K to 500K (and with density ratios of cooling air to free-stream from .3 to 3). Notwithstanding the small test section

(4'x 4'x 36'), at the highest pressure and lowest temperature a Reynolds number of 30,000,000 based on the test section width, can be achieved. (While not a complete duplication of hypersonic conditions and not a substitute for hypersonic tests the capability will also be invaluable in the development of transpiration or film cooling technology for hypersonic applications).

With this range of operating conditions a detailed comparison between measurements and flow field numerical predictions (DNS calculations) at necessarily low Reynolds number can be made. The effects of Reynolds number can then be determined experimentally by systematically raising the pressure and increasing the Reynolds number. It has been intended to use the facility to explore the parameter space, to validate numerical models and to determine the magnitude and spectrum of temperature fluctuations and the resulting fluctuating heat transfer rates, as well as transient effects, which in turn are important in the development of the design and the potential failure mechanisms for integrally woven ceramics. The effects of geometrical variability are also important in design and can be evaluated experimentally and results compared with model predictions.

#### **4. Design and Construction of the Facility**

The mechanical design for the tunnel required particular attention to the high pressure, high temperature requirements, to the test section, to the pump and to the heater. The structure is all T-304 stainless steel and has been welded to meet code requirements for a pressure vessel. A subtlety that led to rework was the fact that the structure is very rigid and to achieve the compliance required for alignment and for gasket seals required special inserts and additional flanges beyond those specified in the initial drawings. The test section required machined surfaces that were made to a fine tolerance so that at three surface junctions leaks could be avoided. Access to the test section was another important design consideration as well as the large diameter, high pressure, high temperature windows. Representative drawings of the test section are attached to this report in Appendix I. Comparable drawings for all components were made prior to component manufacture.

Particular attention was paid to the design of the pump since this application was outside its typical application (i.e. the pump had been designed and used principally for liquid flows and not gases at these temperatures and pressures). The pump design was based on standard incompressible head and flow coefficients but the seal and bearing design required much more attention. Lawrence Pumps developed the mechanical design and with performance guarantees delivered the pump. Under test conditions the bearings failed due to overheating. This required the pump to be returned to the manufacturer and the shaft, bearings and bearing housings were replaced under warranty.

The heater was designed with sufficient power to raise the temperature to 500K in less than three hours. This requires the stainless steel loop to be covered with thermal insulation. At present the insulation has not been applied so that, for safety reasons, as well as the heat loss, the full temperature capability has not been reached. The tunnel has however been taken up to a temperature above 400K at 300psi and with insulation it will

reach the design temperature of 500K. A photograph of the facility, without the fittings for the secondary cooling flow and with the windows removed, is shown in Figure 1.

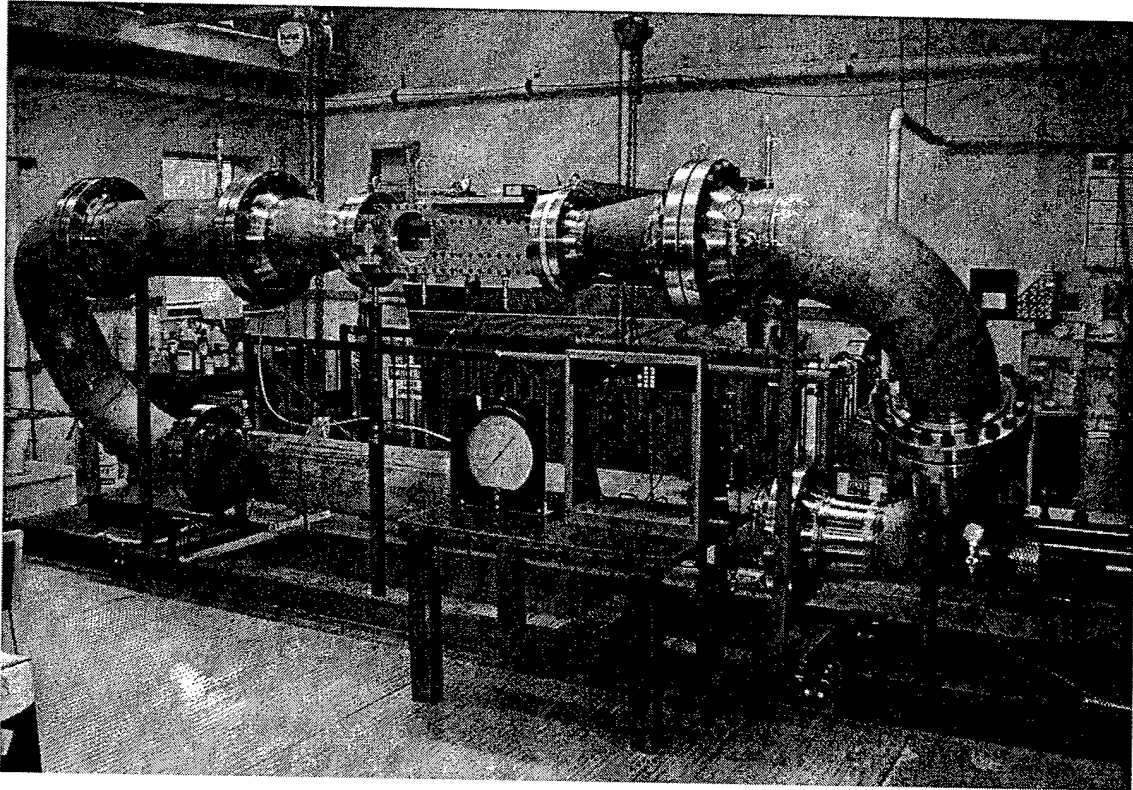
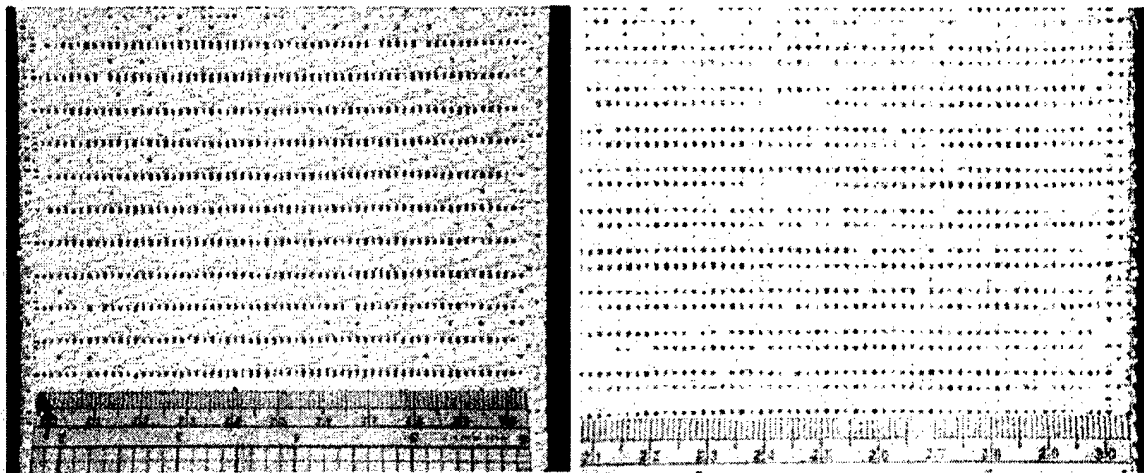


FIGURE 1

The first 4" X 4" sample of integrally woven ceramic material, shown in figure 2, which has been used in the first transpiration cooling experiments, was manufactured by Rockwell Science Center under a companion grant from AFOSR. The figure shows the two sides of the specimen which are approximately .4" apart so that cooling gas can be supplied into the gap between these surfaces. This gap is a set of channels woven into the structure so that the whole structure has rigidity (Figure 4). The specimen was mounted in a ceramic holder and attached temporarily to a lower surface plate so that the cooling gas supplied into the gap between the two surfaces, through the ceramic holder, would transpire only through the upper surface. The upper, transpiring surface that was chosen first is the surface shown on the left in Figure 2. The ceramic holder was then located in a false floor of the tunnel (inside the high pressure lower wall of the tunnel). Photographs of the specimen in the ceramic holder in the test section (with the side wall and end flanges removed) are shown in figure 3 and with one side of the ceramic holder removed in figure 4. The channels for the cooling flow supplied through the ceramic holder can be seen in figure 4. Beneath the specimen is an insulated cavity, between the false floor and the lower high pressure wall of the test section, which supplies the cooling

gas at a pressure above the test section static pressure. This pressure difference determines the velocity of the cooling gas through the transpiring surface.



←→  
Direction of walls

FIGURE 2



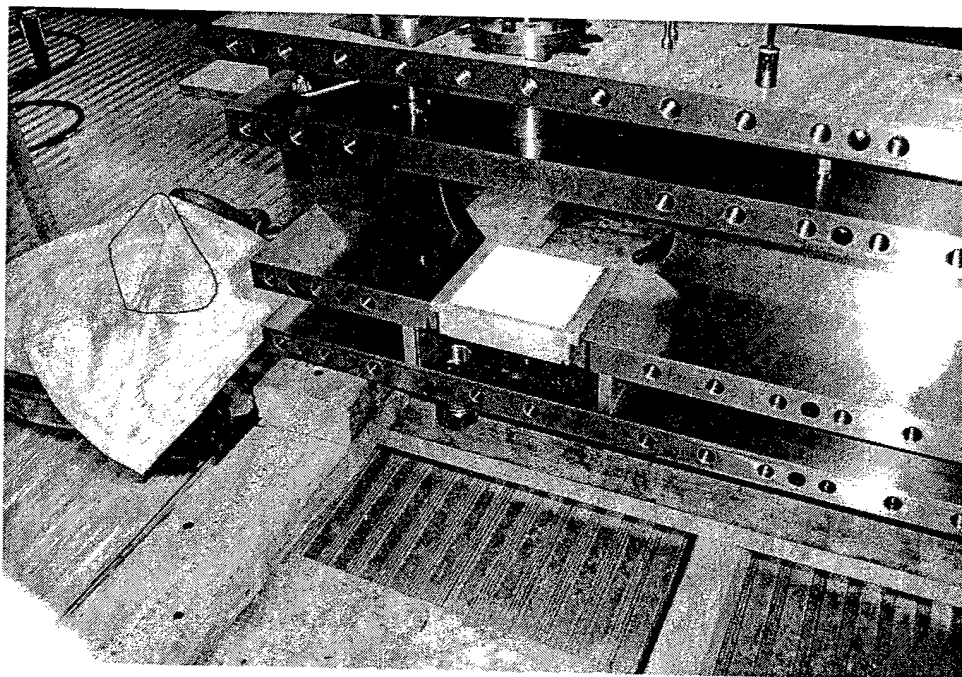


FIGURE 3

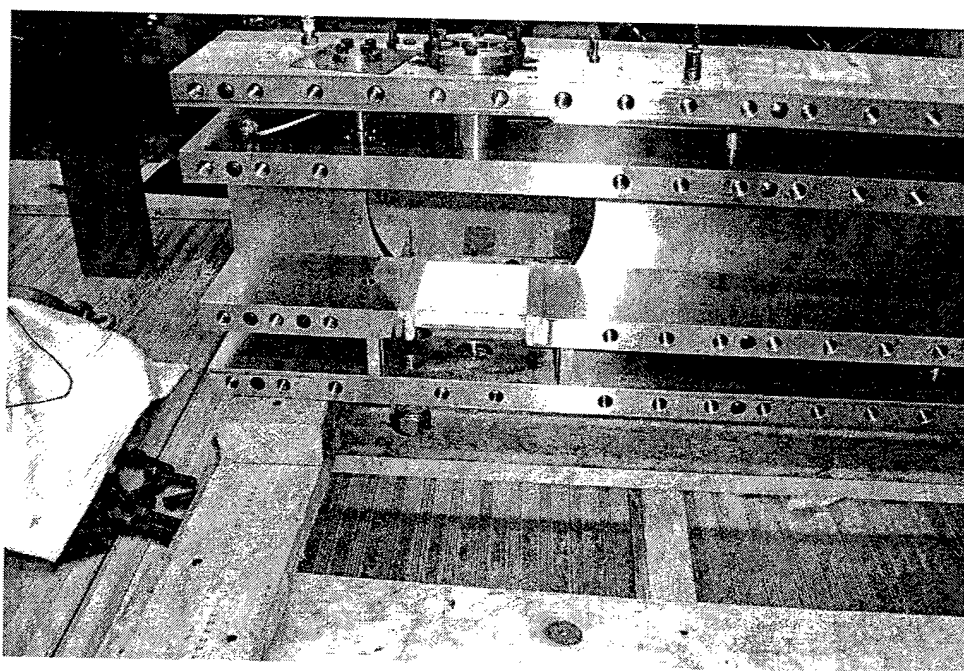


FIGURE 4

The design for the secondary cooling flow system requires a source of cooling gas at the required pressure and temperature. We have used bottled nitrogen in the first instance.

(A bottled supply also allows the density ratio to be partially or wholly obtained by using gases of different molecular weight.). This supply requires a suitable regulator, an on/off valve and a metering valve. The requirements for these components were determined and they were purchased and the system installed and tested. A related and very important issue is the safety relief valve and the exhaust system that will safely regulate the tunnel pressure, for longer run times, while cooling gas is being supplied. At present the safety relief valve is installed but through lack of funds the back pressure regulator and the low temperature cooling system that will reduce the temperature to 200K have been designed but not yet purchased.

## **5. Experimental Results**

The first transpiration cooling experiments using the specimen shown in figures 2, 3 and 4 have been completed. In these experiments measurements of the wall temperature immediately downstream of the transpiring surface (on the centerline and on the surface of the ceramic holder) were obtained for several ratios of cooling surface-jet velocity to free-stream velocity, several free-stream temperatures and cooling gas temperatures and at two different pressures, i.e. 1 and 8 atmospheres. Results are shown in Figures 5, 6, and 7. Figure 5 shows the ratio of surface-jet velocity to free-stream velocity as a function of time. Figure 6 is the corresponding wall temperature as a function of time. Assuming local one dimensional heat transfer and the thermal properties of the machineable ceramic, Figure 7 shows the inferred reduction in heat transfer rate as a function of time. These are preliminary results that require further confirmation. Nevertheless they provide a clear indication of the definitive data that can be obtained and the opportunity that this and much more detailed field data will provide to validate models and better understand the physics of transpiration or film cooling. This data is being compared at present with results of a DNS calculation as described in section 6. It is already clear from the calculations at low Reynolds number that a larger percent open area and a smaller velocity, closer to the friction velocity, offers a substantial improvement in cooling effectiveness for a given cooling volume flow rate.

In the limited time of these experiments shadowgraph flow visualization was attempted but the gradient in refractive index was insufficient to obtain a good photograph of the flow. By using different gases and shadowgraph as well as other flow visualization techniques flow visualization is expected to be a powerful tool in future experiments.

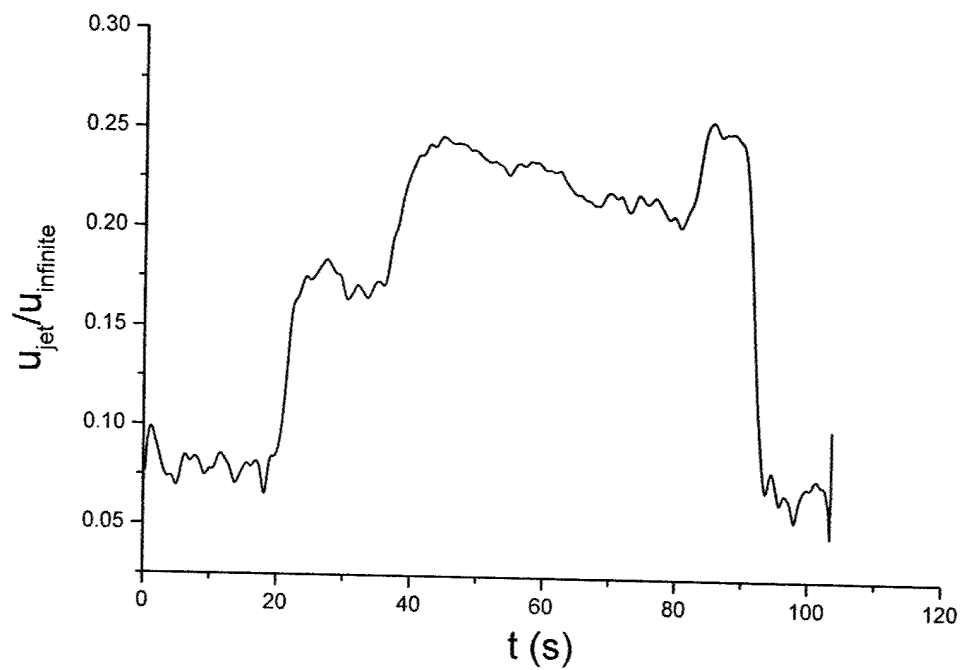


FIGURE 5

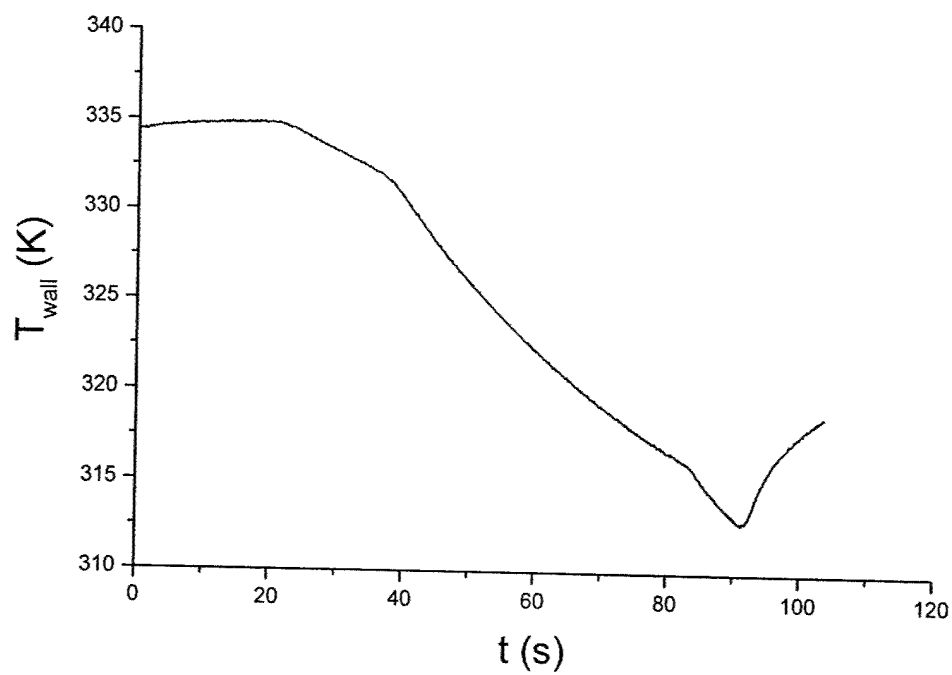


FIGURE 6

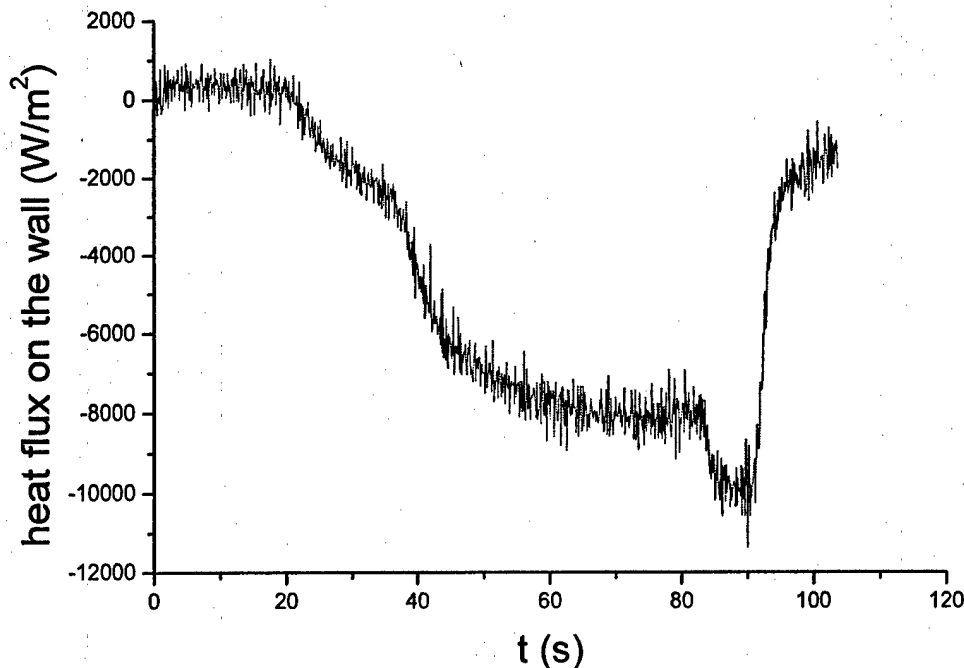
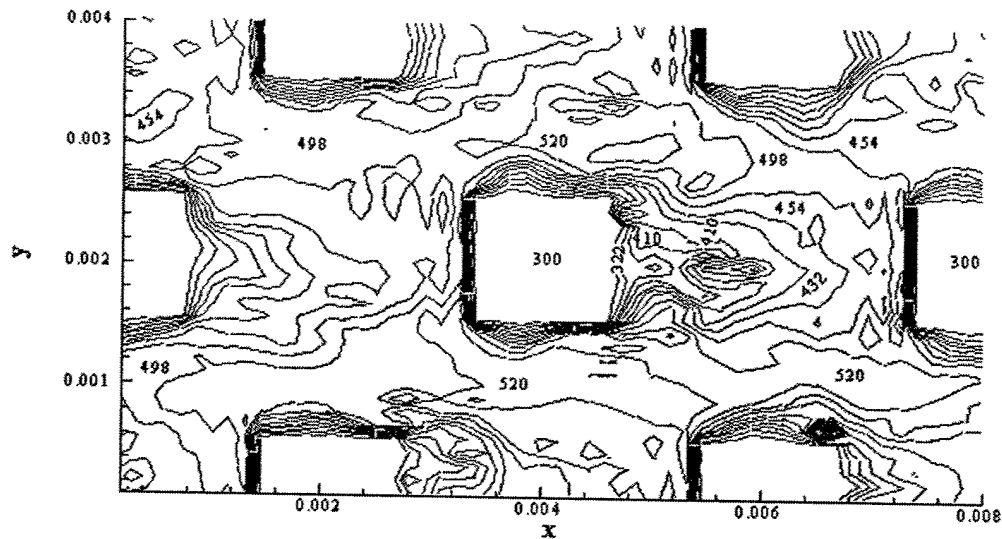


FIGURE 7

## 6. Numerical Developments

In support of the experimental program Professor Brown and Mr. Fengquan Zhong, the graduate student working with Professor Brown, have collaborated with Professor Martin at Princeton and applied the core of Prof Martin's compressible, DNS flow solver to both the spatially developing and temporally developing turbulent boundary layer with transpiration cooling. Mr. Zhong has also worked with Dr Ihab Girgis (a Research Fellow on another program also working with Professor Brown) to obtain an initial mean velocity profile and then new techniques have been developed to establish the required turbulent flow boundary conditions. In particular the viscosity is initially reduced to establish the Reynolds stress and then increased to its correct value in the boundary layer and beyond this value in the free-stream, to damp free-stream disturbances, before again restoring it to its correct value. This rapidly establishes the temporal turbulent boundary layer. For the spatial case at a given time in the temporal calculation the velocity field is then sampled at  $x$  locations and the instantaneous velocities used as the upstream boundary condition for the spatial problem. The value of  $\Delta x$  chosen for the temporal problem is related to the  $\Delta t$  used in the spatial problem using  $\Delta x = .7U \times \Delta t$ . There is therefore an initial adjustment length in the calculation for the spatial problem especially near the wall since the convection speed of near wall structures is less than  $.7U$ . Comparisons with measurements and other numerical predictions in the non-transpiring case have been made. At this early stage of the research the agreement is satisfactory and sufficient for a preliminary extension to be made to transpiration cooling. The interest is to predict the statistics of the transpiring flow field and to find the

geometrical and other parameter trends which are expected to increase cooling effectiveness. The compressible code is intrinsically able to follow the smallest motions of significance in the flow only at low Reynolds number. The intention has been to compare the predictions with experimental results at this same low Reynolds number and then, keeping everything the same but raising the pressure in the facility, to find experimentally the effects of increasing Reynolds number. This too can be compared with early trends predicted numerically. The calculations also enable a study to be made of the trends with parameter changes such as percentage open area, transpiration velocity, geometrical sensitivity etc. This capability allows predictions of surface temperature and temperature fluctuation amplitude and spectrum to be made at low Reynolds number. It is expected that the comparison between these predictions and the experiments will lead to a detailed validation of the model at low Reynolds number, which can then be used with experimental scaling to guide the design for applications. A recent representative example is shown in figure 8 of a flow field calculation for transpiration cooling with a 15% open area, holes normal to the surface and with a free-stream recovery temperature of 600K and a transpiration cooling temperature of 300K. In this case the Reynolds number was approximately 250,000. In this calculation the surface-jet velocity is equal to the undisturbed friction velocity (surface-jet velocity to the free-stream velocity ratio is .06). The corresponding percentage of the surface area (excluding the holes) that is found to be at a mean temperature less than 450K is approximately 30%.



The temperature distribution on the wall

FIGURE 8

A specific calculation using the same transpiration geometry as in the experiment described in section 5 is shown in Figures 9 and 10. In this case the surface-jet velocity is three times the friction velocity in the non-transpiring case, the percentage open area is 7.8% and the free-stream is at 300K and the cooling flow at 280K. In this case, from the surface temperature predictions for an adiabatic wall as in Figure 9, the fraction of the surface area at a mean temperature less than 290K is only 7%. The benefits of the larger percentage open area can be seen from a comparison between this case and the earlier calculation with 15% open area and a surface-jet velocity that in terms of the friction velocity is one third as large as this smaller percentage open area case. Detailed comparisons with the experimental results have not yet been made. Figure 10 shows instantaneous streamlines in a y-z plane normal to the flow (in the x direction) for this 7.8% open area case. The relatively poor performance in this case may not be surprising given the evidently strong mixing.

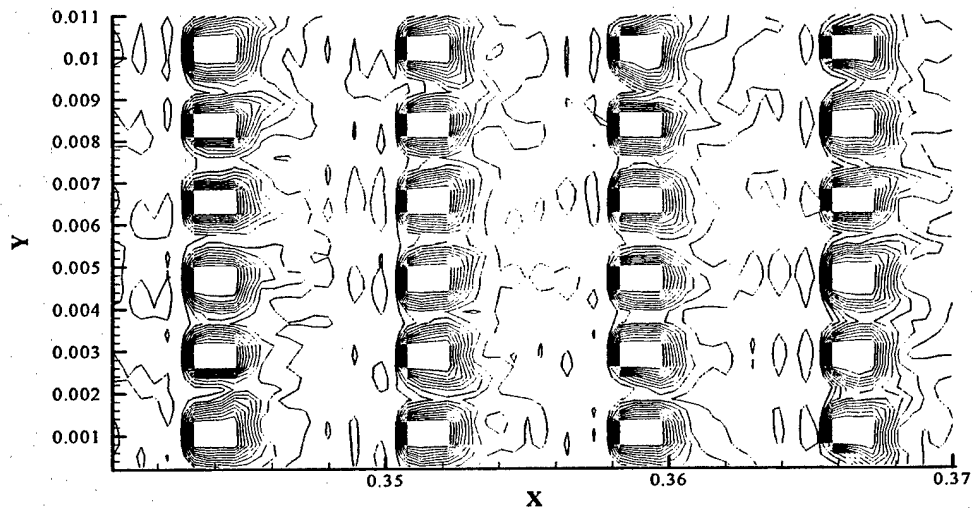


FIGURE 9

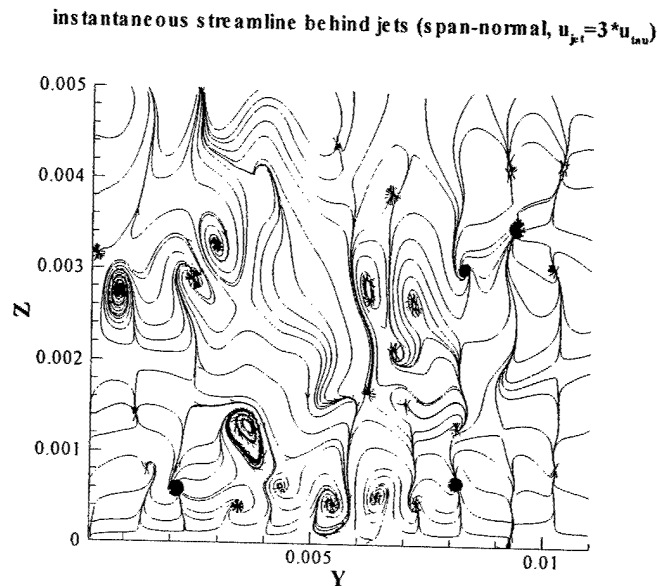


FIGURE 10

## 7. Summary of Accomplishments

A substantial and unique facility has been designed and built at Princeton for the study of transpiration and film-cooling, heat transfer. It can duplicate the density ratio, temperature ratio and Reynolds number at the conditions of the gas turbine combustor application and allows the flow field and temperature for 4"x4" specimens of a woven ceramic material (or any other material) to be measured with various transpiration to free stream velocity and temperature ratios. The flow field is very well defined. The facility is operational and has been run at up to 300 psig, to 400K and 35 m/s at the design pump speed of 4000rpm. The full temperature capability of 500K is expected to be reached with insulation and heater control which have been designed but not yet purchased through lack of funds. There were numerous problems to be overcome in the design and construction of the facility and this led to some rework of the pump (under warranty) and re-machining of components that were made by subcontractors and this correspondingly led to delays in the completion of the construction. It was also more expensive to build it than initially estimated.

The facility has been commissioned and run with the transpiring specimen supplied by Rockwell Science Center. Measurements of surface temperature at a range of velocity ratios, at 1 and 8 atmospheres and at several temperature ratios have been obtained. Such results will provide a benchmark against which to validate models and will provide the

experimental data and understanding required to optimize the many parameters of the material design.

The new facility (with its insulation) will also enable fundamental studies of wall bounded flows, with and without transpiration (or film cooling), and free turbulent flows over a very wide range of Reynolds number (four orders of magnitude) with the same model.

The development of a DNS calculation to model the temporal and spatial transpiration cooling of a turbulent boundary layer at relatively low Reynolds number is now well advanced. This research has already indicated the magnitude of the cooling effectiveness for two different geometries and is expected to indicate parameter trends that are likely to increase the effectiveness of the cooling for a given flow rate.

There has been an early transition of the technology which has preceded these steps because of the promise of the technology.

## **5. Personnel Supported**

Garry Brown, Professor Princeton University Princeton, NJ

William Stokes, Senior Technician, Princeton University, Princeton, NJ

Fengquan Zhong, Graduate Student, Princeton University, Princeton, NJ

## **6. Publications**

No Publications to date

## **7. Interactions/Transitions**

This research is closely coupled with the continuing research led by Dr. Brian Cox of Rockwell Science Center and supported at the same time as this Grant through a companion AFOSR Grant. It represents perhaps the first and strongest cross-disciplinary effort in transpiring structures. It involves both a new technology for transpiration cooling and ceramic composite design and textile composite mechanics. Preliminary work has confirmed the substantial benefits which this technology could provide. As a result there has been an early transition, particularly through Dr Roquemore at AFRL, to develop and assess actual hardware in a combustor rig as illustrated in Figure 11. A close relationship with Dr. Mel Roquemore of WPAFB has been established.



## Basic Research Problems in Mechanics and Heat Transfer for Integrally Woven, Transpiration Cooled Ceramic Composite Turbine Engine Combustor Walls

Programs for transition of basic science to new combustor development

### Programs (AFRL Propulsion & Materials Directorates):

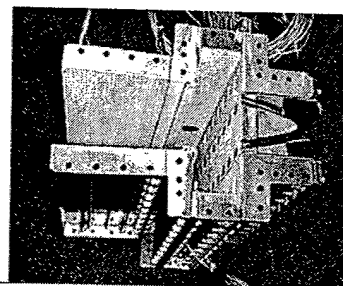
- AFRL SBIR (via TK Engng; with GE)  
integrally woven SiC/SiC TVC liner
- AFRL PRDA (Dr. Mel Roquemore; with Williams Intl)  
integrally woven all-oxide combustor liner

### Proposal (DoE Nat. Energy Tech Lab):

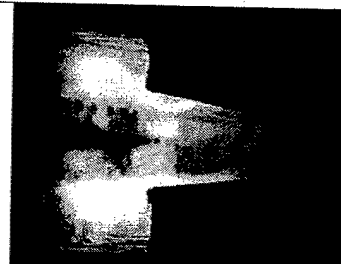
- land-based power generating turbine engines  
(Udaya Rao; with Solar)

### Goals:

- fabricate integrally woven transpiring SiC/SiC & all-oxide TVC combustor components
- acquire performance validation in burner test rigs at AFRL (Roquemore) and Solar
- demonstrate design envelope in realistic test conditions
- *virtual design based on basic AFOSR studies & modeling tools*



Trapped Vortex Combustor



Roquemore et al., 2001- WPAFB

FIGURE 11

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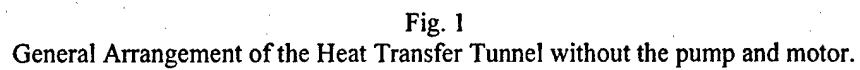
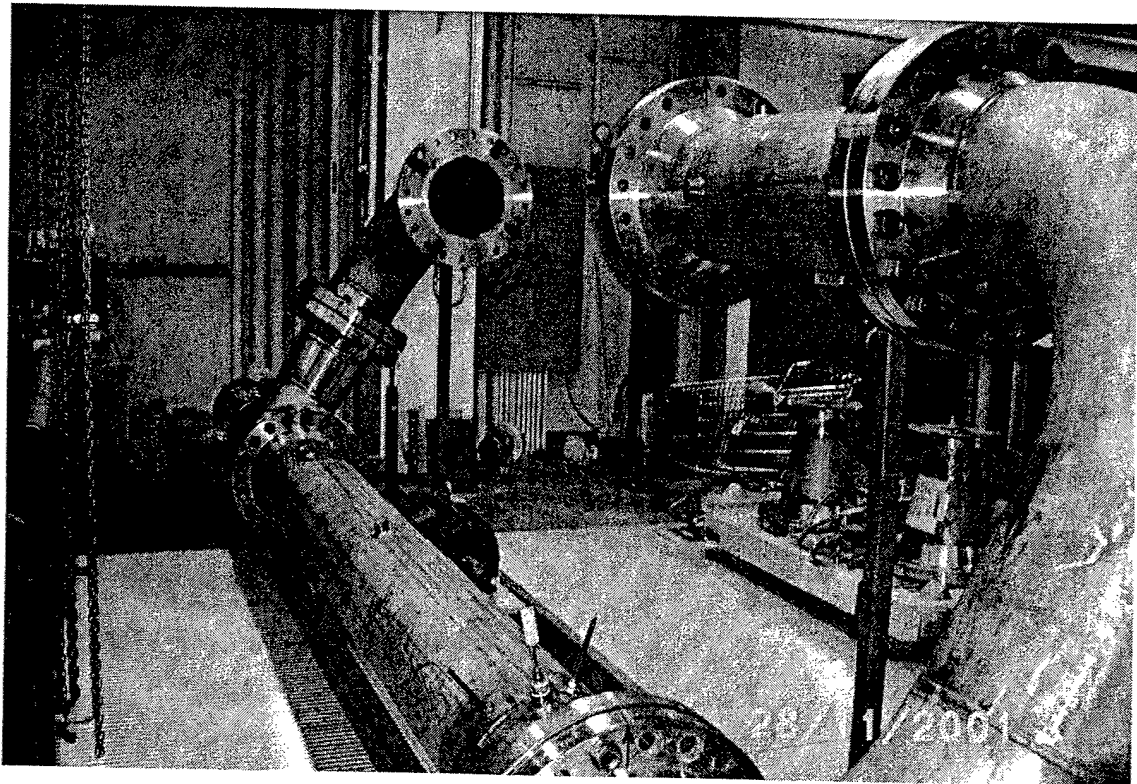
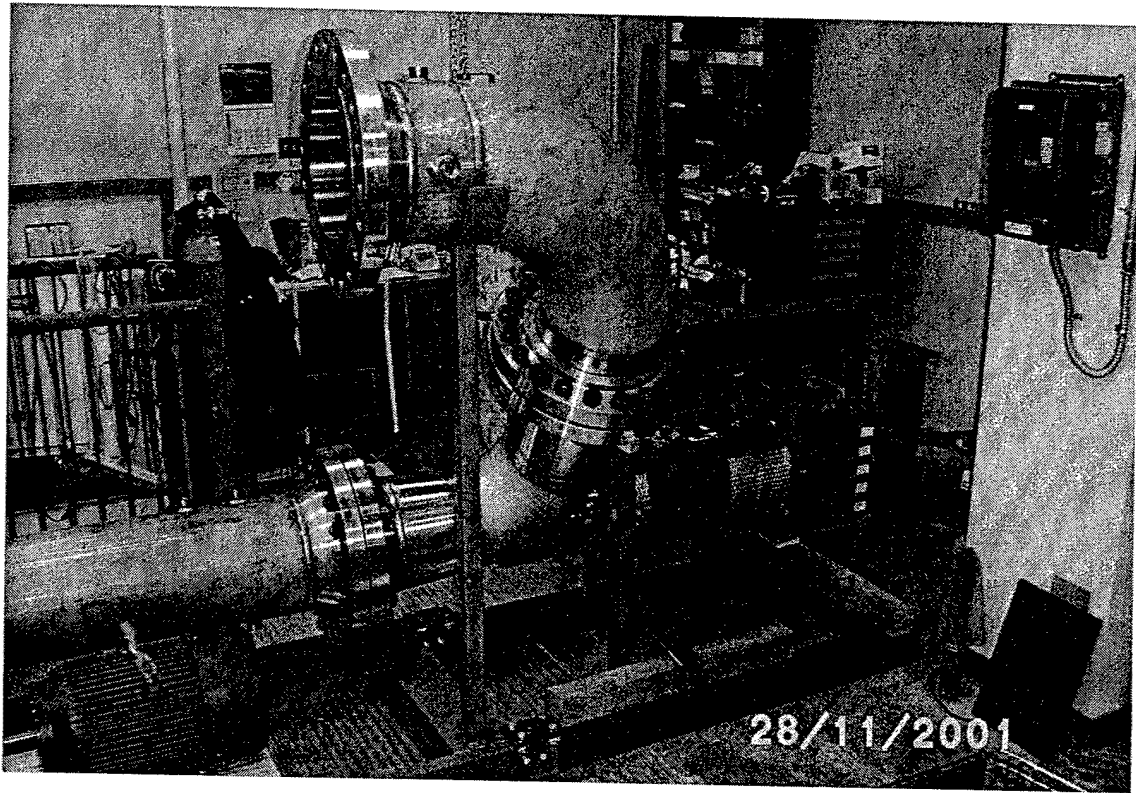


Fig. 1



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**Fig. 3**  
**Heat Transfer Tunnel**  
**Test Section Top Outer Wall**

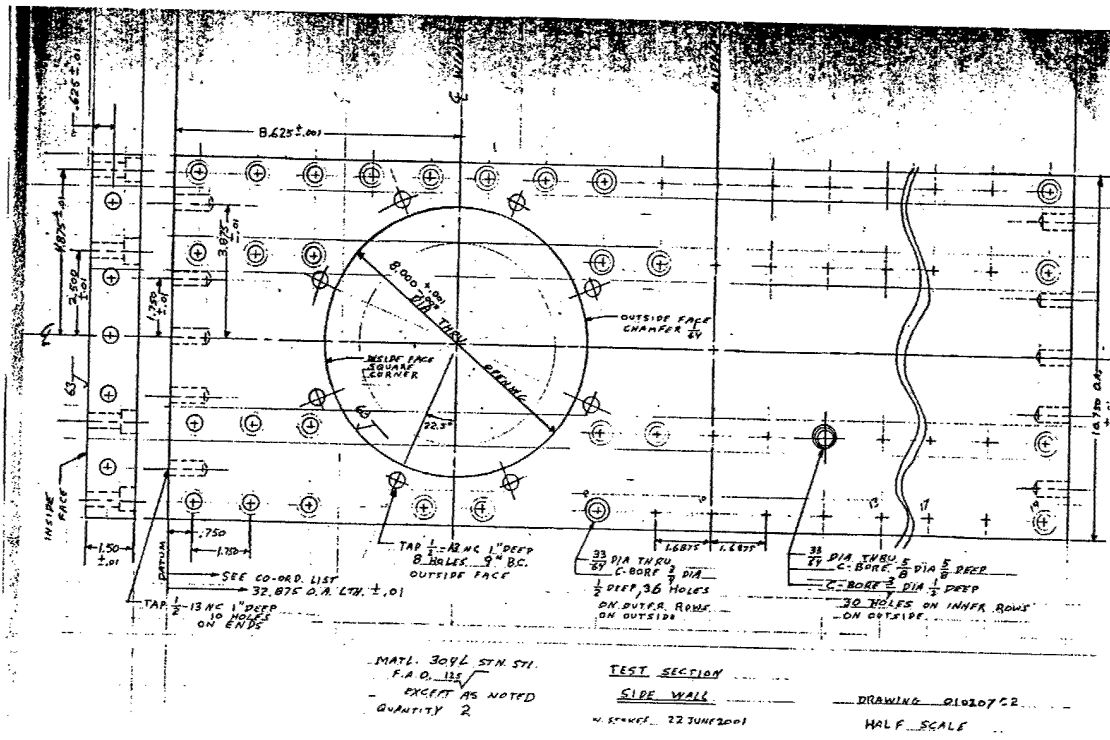


Fig. 4  
Heat Transfer Tunnel  
Test Section Side Wall

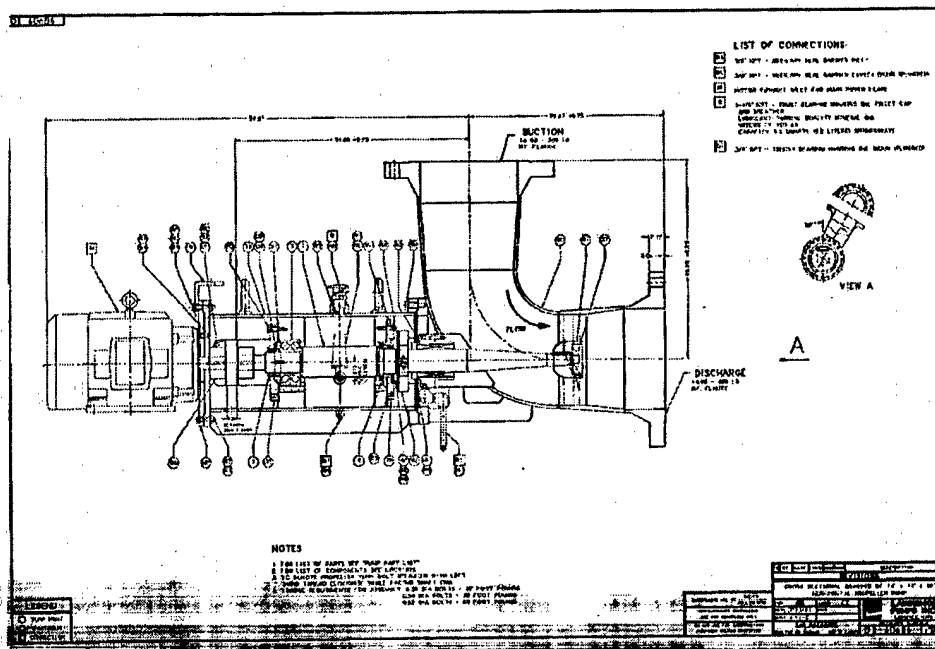


Fig. 5  
Heat Transfer Tunnel Pump